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ABSTRACT

While global sea level has risen by 20 cm since the mid-19th century, the role of this process in present-day and past shoreline mobility is still debated. In this paper, we review previous studies that explored the relations between sea-level rise and shoreline changes over the last few decades. Existing methods can be classified into two groups: (1) approaches based on the analysis of trends and variability in shoreline change observations, which investigate whether a correlation with the temporal or spatial patterns sea level changes can be established; and (2) approaches based on the comparison of shoreline observations with a coastal model outcome, which attempt to evaluate the contribution of sea-level rise to shoreline mobility using coastal evolution modeling tools. The existing applications of these methods face two common difficulties: first, shoreline data are often lacking or insufficiently resolved temporally to capture the dynamics of coastlines; and second, relative sea level along the coast is generally only known in a limited number of areas where tide gauges are available. These two challenges can be met, owing to the increasing amount of shoreline change observations and complementary geodetic techniques. The wide range of different interpretations regarding the role of sea-level rise in recent shoreline changes highlights the necessity to conduct specific studies that rely on local observations and models applicable in the local geomorphological context.

Contents

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1. Introduction

Since the late 19th century, global sea level has risen by about 1.6 mm/yr (Church and White, 2011), whereas its rate did not exceed 0.6 mm/yr during the two previous millennia (Kemp et al., 2011). At timescales ranging from decades to centuries, sea level primarily varies because of anthropogenic climate change and its impacts on ice melt and the warming of the oceans (Milne et al., 2009; Church et al., 2011). As sea level is expected to rise further in the future (0.5 to 1 m by 2100 and possibly more, Church et al., 2013), there are increasing concerns about its potential future impacts on coastal zones (e.g., Hinkel and Klein, 2009; Hinkel et al., 2010; Nicholls and Cazenave, 2010; Nicholls, 2011; Hallegatte, 2012; Hinkel et al., 2012; Hallegatte et al., 2013; Mimura, 2013).

One of the expected consequences of sea-level rise is the retreat of shorelines, due to permanent passive submersion (which may affect flat and low-lying areas such as wetlands) or coastal erosion (e.g. Bird, 1996; Stive et al., 2002). The former indicates a retreat of the shoreline caused by an increase in sea level that does not necessarily cause a change in morphology, while the latter commonly refers to a range of different processes that cause morphological changes, such as: coastal sediment redistribution due to waves and currents and their interactions with human intervention (e.g., Slott et al., 2010) or biological processes (Gedan et al., 2011; Storlazzi et al., 2011) as well as other processes affecting coastal cliffs such as abrasion and hydrogeological processes (Regard et al., 2012). The term erosion is also used as a quantitative measure of different variables: the volume or mass of sediments removed from the nearshore zone, or retreat of the shoreline as measured by a wide range of indicators (Boak and Turner, 2005). Hence, passive submersion and coastal erosion can be differentiated by the movement of a volume of sediments, which may be lost from the coastal sediment budget or even redistributed (landward or seaward), but both processes may result in shoreline retreat. Sea-level rise is not a unique process causing shoreline change: instead, numerous factors and processes acting at different spatial and timescales are involved in causing shoreline changes (Bird, 1996; Stive et al., 2002; Fig. 1) and the various types of coastal systems are not expected to respond similarly to the same rates of sea-level change (e.g., Gornitz, 1991; Fletcher, 1992).

While coastal evolution at decadal to multi-decadal timescales remains difficult to predict (Woodroffe and Murray-Wallace, 2012), significant shoreline retreats are expected over the next centuries as sea-level rise will likely exceed 1 m in some locations (Schaeffer et al., 2012). Hence, many coastal sites may experience several transitional stages over the next few centuries: during the first phase, the impact of sea-level changes may remain less significant than those of other coastal processes; then, during a second phase, sea-level rise should significantly exacerbate coastal erosion; and finally, during a third phase (most likely after 2100), sea-level rise may reach several meters and many low lying area may be permanently inundated or dyked and drained. Through an analytical analysis of coastal evolution equations, Stive (2004) suggested that with current sea-level rise rates, most coastal beaches should be presently experiencing the first phase or the early stages of the second phase. The question arises as to whether this statement is confirmed by observations. This question was previously addressed by Bird (1985): by collecting shoreline change observations worldwide in the late 70s and early 80s, he noticed that most of the investigated coastal sites (in particular, 70% of beaches) were eroding. However, he could not find any clear relation between the spatial patterns of global coastline changes and those of relative sea-level rise, suggesting that global sea-level rise is not the unique cause of the global eroding crisis (Bird, 1985, 1987, 1996). Other studies suggest that even moderate rates of sea-level rise can cause significant shoreline retreat (e.g. Zhang et al., 2004), so that what remains unclear is to what extent slight changes of sea level on the order of a few mm/yr have affected shorelines over the last several decades.

This paper reviews existing studies looking at observational evidence of the recent impacts of sea-level rise on the evolution of shorelines over the last few decades. As different conclusions have been drawn from existing studies, we analyze especially the methods, which can be classified in two groups: (1) methods based on the analysis of observations of shoreline changes only (data-based approach, part 2); and (2) methods based on the comparison of

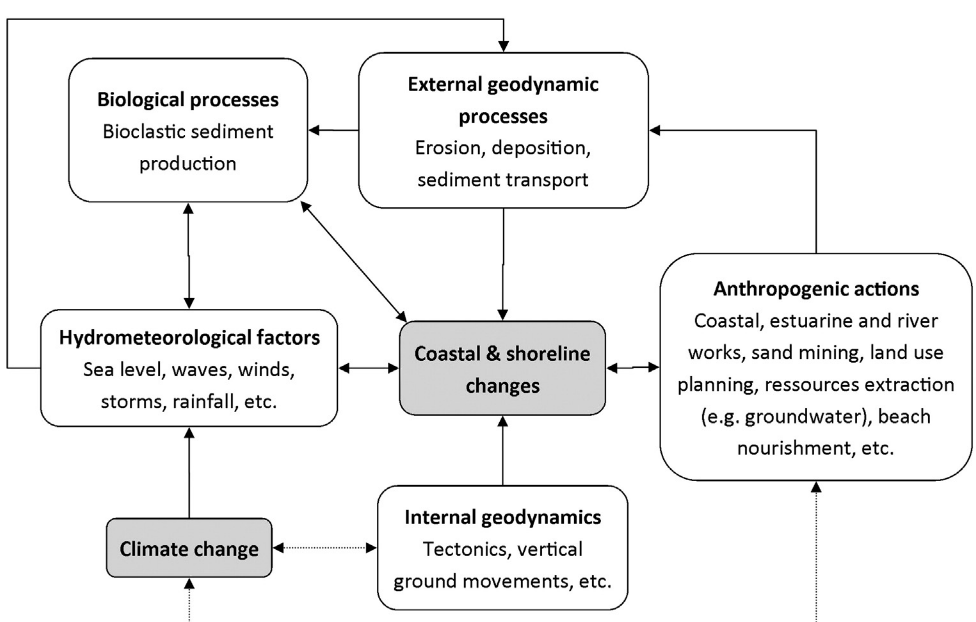

Fig. 1. Different categories of factors and processes involved in shoreline changes. Interactions and feedbacks between these factors are indicated by arrows. Because of the multiplicity of factors, processes, interactions and feedbacks, the attribution of shoreline change to one or several causes is complex and difficult.
After Bird (1996), Stive (2004) and Garcin et al. (2011).

Table 1
List of reviewed studies analyzing potential relations between the spatial patterns of sea-level rise and those of shoreline changes. Shoreline change database refer here to datasets constituted from both in-situ measurements and remote sensing images.

Site	Coastal geomorphology	Study	Approach	Source of shoreline change data	Source of sea-level rise data	Conclusion on the role of sea-level rise (SLR)
Eastern coast of USA	Beaches	Zhang et al. (2004)[a]	Statistical analysis of a large dataset: comparison of observed shoreline changes in similar coastal sites	19th and 20th centuries shoreline change database	Several tide gauges	SLR ultimately responsible for shoreline erosion in the eastern USA coast
West-central Pacific	4 urbanized and natural atolls islands in western Pacific	Webb and Kench (2010)	Observation and analysis of causes of shoreline changes	Surface changes from remote sensing data over 19 to 61 years	Tide gauges	Reef islands are not necessarily eroding in response to recent sea-level rise
South-east Asia	5 deltas in south-east Asia	Shearman et al. (2013)	Observation and analysis of causes of shoreline changes	Surface changes from remote sensing data over 20 to 35 years	Satellite altimetry; analyses of possible human-induced causes of subsidence	SLR possibly affecting shoreline retreat in two estuaries of Papua-New Guinea
French Polynesia	4 atolls with moderate human pressure	Yates et al. (2013), Le Cozannet et al. (2013)	Observation and analysis of causes of shoreline changes	Surface changes from remote sensing data over 40 to 50 years	Sea level reconstructions; use of previous work on regional ground movement	No observational evidence of the role of sea-level rise
Hawaii	Beaches on 2 islands	Romine et al. (2013)	Observation and analysis of causes of shoreline changes	20th centuries shoreline change database (extended from Fletcher et al., 2012)	Tide gauges	Different rates of SLR are the most likely cause of the different historical shoreline changes in the two islands considered
New Caledonia	12 estuaries with moderate direct human pressure	Garcin et al. (2013)	Statistical analysis of a large dataset: search for correlations	Surface changes and limit of sediment deposits over 65 years	Geomorphological indicators, tide gauge measurements	SLR is less important than other factors (sedimentary supply due to open cast mining)
Eastern coast USA	Multiple types: cliffs, wetlands, beaches	Guttierrez et al. (2011)	Statistical analysis of a large dataset using Bayesian networks	20th century Shoreline change database (Thieler and Hammar-Klose, 1999)	Interpolation of tide gauge data	SLR is the most important factor in the model
Europe	Multiple types, not considering developed coastlines	Yates and Le Cozannet (2012)	Statistical analysis of a large dataset using Bayesian networks	European coastal database — shoreline changes representative of one decade (1990s) www.eurosion.org	Interpolation of tide gauge data	SLR is the second most important factor in the model
Shoreline change data collected around the world	Multiple types	Bird (1985)	Collection of observations and analysis of causes of shoreline changes	Shoreline changes over past few decades, depending on data availability.	Information from tide gauge data and regional to local geological analysis	Many factors are involved in shoreline changes. No evidence of the impacts of sea-level rise can be clearly demonstrated

[a] Denotes that only a part of the study falls within this type of approach.

Table 2
List of reviewed studies analyzing potential relations between the temporal dynamics of sea-level rise and those of shoreline changes. Shoreline change database refer here to datasets constituted from both in-situ measurements and remote sensing images.

Site	Coastal geomorphology	Study	Source of shoreline change data	Source of sea-level rise data	Conclusion on the role of sea-level rise (SLR)
Marshall islands, western Pacific	1 atoll with moderate human pressure	Ford (2013)	Up to 8 shoreline positions over 67 years from remote sensing images	Tide gauges on two atolls located ~270 km away	A recent erosional shift is observed. This could be related to global sea-level rise, natural variability of shorelines, or to sampling issues.
Trinidad and Tobago in the Caribbean Sea	Beaches	Singh (1997)	Decadal beach profile data completed with markers and interviews to evaluate longer term shoreline change rates	Tide gauge data: relative sea level is significantly exacerbated by land subsidence	Beaches are eroding relatively rapidly and erosion is accelerating. It is suggested to be related to relative sea-level rise.
French Guyana	Mangroves on alongshore migrating mud banks	Gratiot et al. (2008)	Up to 39 shoreline positions over 20 years from remote sensing images	Tide gauge	The periods of erosion and accretion correlate with the tidal cycle of 18.6 years.
Louisiana (USA)	Mississippi–Alabama Barrier islands	Morton (2007); Morton (2008)	Shoreline changes database representing about 4 to 10 shoreline positions over 150 years	Tide gauge data: discussion of potential subsidence	There is no observation of an increase in subsidence that can account for the observed acceleration in shoreline erosion. Conversely, the historical reduction of sand available for longshore coastal sediment transport processes is well correlated with the observed trends.
Louisiana (USA)	5 wetland areas	Morton et al. (2005)[a]	Remote sensing images covering 48 years	Geomorphological indices	The dynamics of wetland losses and passive submergence are temporally and spatially consistent.

[a] Denotes studies that also refer to spatial patterns to establish a relation between shoreline changes and sea-level rise.

observations with model outcomes (model-based approach, part 3). Part 4 first examines common limitations in the two important datasets required in these approaches (shoreline and relative sea level data) and then proposes approaches for future applications of the two previous methods to different types of coastal environment. Finally, part 5 examines the initial lessons that can be learnt from the reviewed work.

2. Methods based on observations only (data-based approaches)

This part reviews studies that have attempted to estimate the impact of decadal to multi-decadal sea-level changes on shoreline mobility by analyzing observations only. The principle of these methods is to examine if a relation can be found between the spatial or temporal variability of sea-level rise and those of shoreline changes, or if other factors causing coastal evolution can be identified. The two next sections examine the methods and results of studies based on the analysis of spatial patterns (Table 1) and of the temporal dynamics (Table 2) of sea level and shoreline changes.

2.1. Methods analyzing potential relations between the spatial patterns of sea-level rise and those of shoreline changes

The principle of methods based on spatial patterns is to compare how similar coastal environments have evolved under different sea-level rise rates. These methods use the fact that sea level variations, as felt at the coast, display regional variability (e.g. Tamisiea and Mitrovica, 2011; Meyssignac and Cazenave, 2012; Stammer et al., 2013) and can also vary locally as they integrate more local vertical land motions (uplift or subsidence), which increase or decrease the relative sea level changes, i.e., as felt at the coast (Woppelmann et al., 2009; Ostanciaux et al., 2012; Santamaria-Gomez et al., 2012; Woppelmann and Marcos, 2012).

Depending on the number of coastal sites considered and on the complexity of the sedimentary mechanisms involved, several types of methods have been used (Table 1). In its most common form, the approach of these studies is a qualitative analysis of coastal geomorphic and hydrologic observations, aiming to elaborate a comprehensive scheme of the physical processes and human activities at work in the

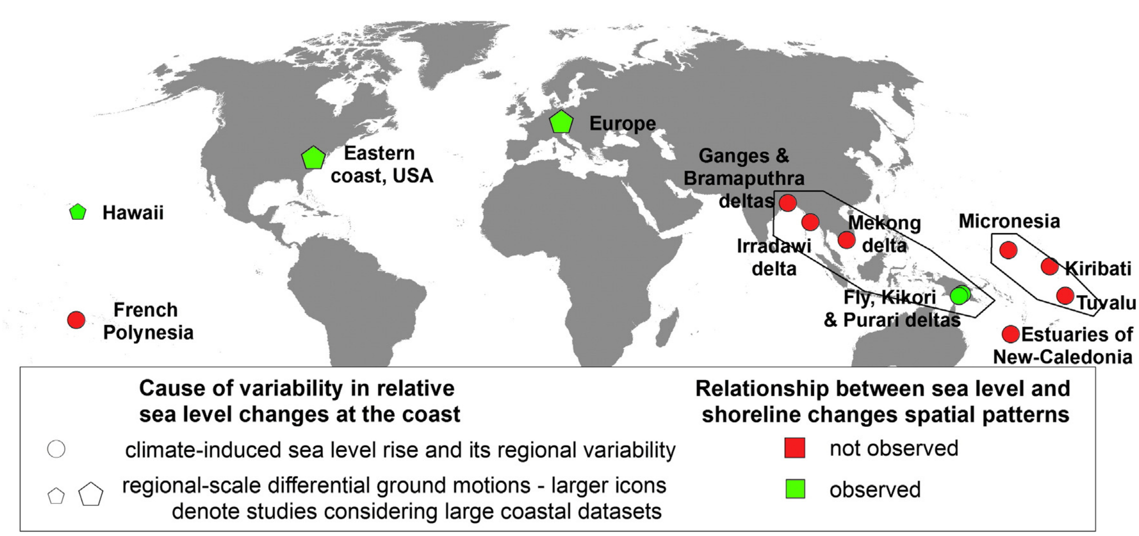

Fig. 2. Results of observation-based studies based on spatial patterns; boxes indicate coastal sites analyzed within the same study (e.g. Shearman et al. (2013) examined 6 deltas).

coastal zone and in the related watersheds (Webb and Kench, 2010; Yates et al., 2013; Romine et al., 2013; Shearman et al., 2013). This protocol is not necessarily always applicable in practice and the existing data may not clearly indicate why the shoreline has changed or remained stable. This first qualitative approach is therefore adapted when the causes of changes are relatively obvious to observe, and data are available.

As the amount of coastal data to be analyzed is growing, the qualitative approach becomes difficult to apply. To extract information from larger coastal datasets, several methods can be applied, from looking for correlations between variables (Garcin et al., 2013) to more advanced statistical approaches: Gutierrez et al. (2011) proposed to model the relations between shoreline mobility and its causative factors using Bayesian networks. They used coastal observations to calculate the parameters of the Bayesian network (i.e. the conditional probabilities linking variables such as the probability of erosion given the geomorphology, the wave and tidal climate, sea-level rise, etc.), and used the developed network to perform retrospective predictions of observed shoreline changes. They finally interpreted performance scores of the Bayesian network as indicators of the relative importance of each variable in the model (Hapke and Plant, 2010). This approach highlights the existing statistical links between variables (including variables representing the spatial variability of sea-level rise and shoreline evolution) and provides a way to extract synthetic statistical information from very large coastal datasets, such as those collected by Quelennec et al. (1998), Thieler and Hammar-Klose (1999), and Eurosion (2004).

Table 1 and Fig. 2 show not only that the number of studies applying an approach based on the analysis of spatial patterns is limited, but also that different types of results have been obtained from the application of methods based on spatial patterns. In some cases, a relation between shoreline changes and the rates of sea-level changes has been identified (Zhang et al., 2004; Gutierrez et al., 2011; Yates and Le Cozannet, 2012; Romine et al., 2013; Shearman et al., 2013). For example, Shearman et al. (2013) suspect that different rates of multi-decadal sea-level rise account for different coastal responses in some Asian deltas. In particular, they highlight that the only possible cause of the retreat of delta shorelines in Papua New Guinea seems to be climate-induced sea-level rise. Romine et al. (2013) provide the same type of argument to conclude that the most likely cause of two Hawaiian islands being affected differently by coastal erosion is that they are affected by different relative sea-level rise rates. In both cases, the role of sea-level rise is demonstrated by the absence of evidence that other processes caused shoreline changes. The East Coast of the USA is also an example where the regions affected by the highest sea-level rise rates are also those affected by the fastest shoreline retreat rates (Zhang et al., 2004; Gutierrez et al., 2011). Similarly, the Eurosion coastal dataset (http://www.eurosion.org) indicates that the uplifting coasts of Scandinavia are also mostly showing shoreline advance (Yates and Le Cozannet, 2012). Many of these examples have suggested that relatively moderate changes of sea level (on the order of a few millimeters per year) can cause significant shoreline changes. However, other studies found no clear relation between the spatial patterns of shoreline change and those of shoreline mobility (Webb and Kench, 2010; Yates et al., 2013; Le Cozannet et al., 2013). In these studies, other more prominent causes of shoreline change have been found such as the effects of storms and human activities. Such results indicate that the actual role of sea-level rise could not be detected within the noise of shoreline mobility for the particular sites investigated (Yates et al., 2013; Le Cozannet et al., 2013) and that shorelines do not necessarily retreat when sea level is rising (Webb and Kench, 2010).

It might be questioned why some studies find a relation between spatial patterns of sea-level rise and shoreline changes whereas others do not. If we exclude the possibility that all relations found are random, the differing results might illustrate the fact that shorelines may respond differently even to the same rates of sea-level changes, depending on the local and regional coastal setting. We also note that for most instances where sea level changes are identified as a significant cause of shoreline mobility, the spatial variability of relative sea level changes at the coast is actually a consequence of ground movement (Fig. 2). For example, differing rates of relative sea level changes along the eastern coast of the USA and of Europe are the consequence of the Global Isostatic Adjustment (Peltier, 1999; Tamisiea, 2011), causing subsidence around the Chesapeake Bay and uplift in Scandinavia. The ground movement started long before sea level started to rise again in the late 19th century due to human-induced climate change, suggesting that the cumulated effects of sea-level changes (and not only their rates) play an important role in the results of studies listed in Table 1.

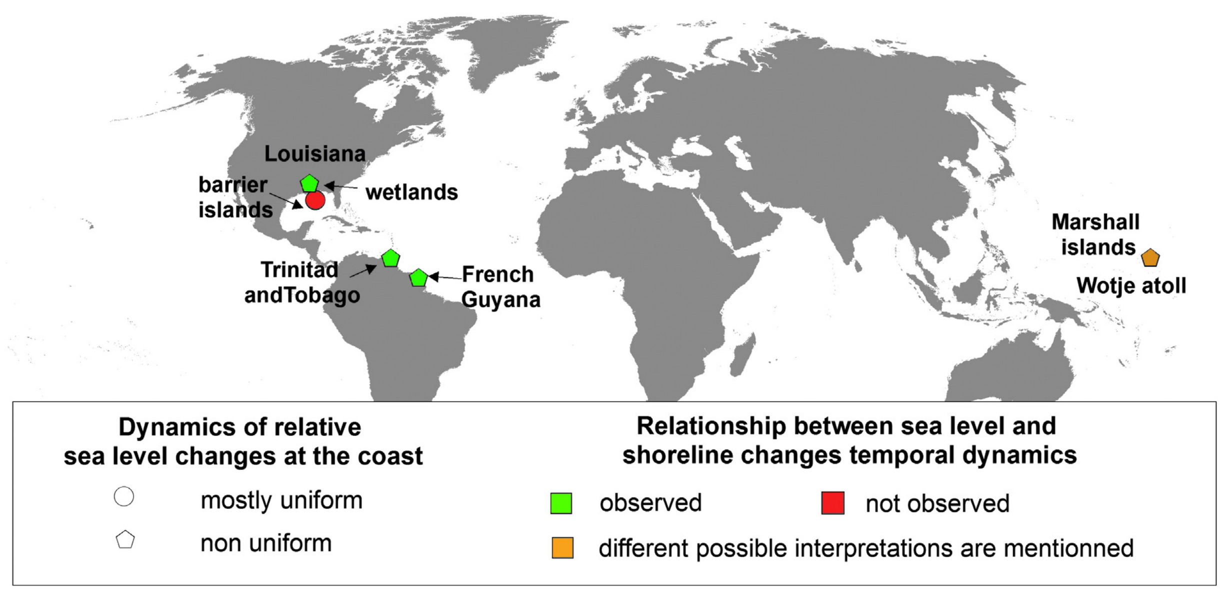

Fig. 3. Results of observation-based studies based on the analysis of the temporal dynamics of shoreline changes and sea-level rise; non uniform coastal sea-level changes here are caused by the El Niño Southern Oscillation (Ford, 2013), the 18.6-year oscillation in tides (Gratiot et al., 2008), or ground subsidence related to oil extraction (Singh, 1997) or mining activities (Morton et al., 2005).

However, since only a very limited number of coastal sites are analyzed in Table 1 and the related studies, more research is needed to test such hypotheses.

2.2. Methods analyzing potential relations between the temporal dynamics of sea-level rise and those of shoreline changes

In contrast to the previous approach, methods analyzing temporal patterns examine whether the temporal dynamics of shoreline changes are similar to those of sea-level rise, or to those of any other factor affecting coastal changes. Several studies have used this principle to examine if sea level changes are the main cause of shoreline evolution (Table 2). For example, Singh (1997) cautiously suggested that increased rates of shoreline change could be related to the acceleration of coastal subsidence related to oil extraction in Trinidad and Tobago. Morton et al. (2005) and Morton (2007, 2008) also used this approach to identify the main causes of land losses in coastal wetlands and on sandy barrier islands of Louisiana, Alabama and Mississippi (Northern coast of the Gulf of Mexico). They found that the temporal dynamics of land losses in wetlands are temporally (and spatially) consistent with the increase in subsidence due to anthropogenic activities. However, they were unable to find a similar relation on the Louisiana sandy barrier islands: there, the increase in erosion rates on these islands was found to be consistent temporally with a reduction in sediment availability. Therefore, in this case, the uniform rise of sea level observed at tide gauges located nearby was unlikely to be the main reason for increased land losses on these barrier islands. The approach based on the analysis of temporal patterns has also been applied to the coastal mud banks of French Guyana (Gratiot et al., 2008) and at the Wotje atoll in the Marshall Islands (Ford, 2013), with two different interpretations and conclusions. The first study found a relation between the 18.6-year oscillation in tides and shoreline changes, suggesting that mangroves are very sensitive to slight changes in sea level. The second study provided evidence of a recent shift toward erosion after decades of accretion or stability at the Wotje atoll. Ford (2013) suggests that this new erosional trend may indicate an adjustment to new forcing conditions (possibly sea-level rise), or the natural decadal variability of shoreline changes in relation to ENSO, or even a sampling issue, as only two shoreline positions could be estimated between 1945 and 1976. This highlights the difficulties of the interpretation stage in observation-based approaches, one important limitation being the lack of data with sufficient temporal resolution and timespan.

Again, the number of studies is limited (Table 2, Fig. 3), and the results obtained suggest that sea-level changes may play a major role in some local coastal settings. Some of the studies reviewed in Table 2 hypothesize that shorelines immediately respond to changes in relative sea-level rise rates (Singh, 1997; Morton et al., 2005; Gratiot et al., 2008). While this seems realistic for rapid rates of sea-level rise (Singh, 1997; Morton et al., 2005; Uehara et al., 2010), a delay between changes in relative sea-level rise and the response of shorelines may be expected. Such a delay in shoreline adjustment to new sea level conditions has been observed by Ballu et al. (2011) after an earthquake that lowered a coastal area by about 1 m in the Torres Islands (Vanuatu). Despite this important assumption regarding the temporal dynamics of the responses to changes in the forcing factors, these data-based approaches analyzing the temporal patterns of change should receive more attention in the future as more numerous high temporal resolution coastal observations are becoming available worldwide.

3. Methods comparing model outcome with observations (model-based approaches)

3.1. Principles and choice of a coastal evolution model

This part examines studies that compared observations of shoreline changes with the outcome of a coastal evolution model (Table 3; Fig. 3). Model-based approaches attempt to separate the contribution of sea-level rise to shoreline change from those due to other factors. In the

Table 3
List of reviewed studies comparing model outcomes with observations.

Site	Coastal geomorphology	Study	Model used to evaluate the impacts of sea level rise	Source of shoreline change data	Source of sea-level rise data	Conclusion on the role of sea-level rise (SLR)
New Jersey, USA	Beaches with coastal defenses	Allen (1981)[a]	Bruun rule	4 to 15 aerial images over 25 years	Tide gauge	SLR accounts for 1 to 3% of observed changes
North Carolina, USA (Outer banks)	Beaches on barrier systems	Inman and Dolan (1989)[a]	Bruun rule	Shoreline changes database covering 42 years	Tide gauge	SLR accounts for 21% of observed changes
Eastern coast, USA	Beaches with few human interventions	Zhang et al. (2004)	Bruun rule	19th and 20th centuries shoreline change database	Tide gauges	Relative agreement between Bruun rule and observed erosion
eThekwini municipality, South Africa	Beaches	Corbella and Stretch (2012)[a]	Bruun rule	4 to 18 beach profiles over 20 to 37 years	Tide gauge	SLR accounts for a significant part of shoreline erosion
Skallingen, Denmark	Beaches on a tidal inlet	Aagaard and Sørensen (2013)[a]	Bruun rule	Yearly rates obtained from a shoreline database covering the last 40 years of the inlet's shift toward erosion (with complementary data dating back up to the early 19th century).	Tide gauge	Minor role
Spanish Basque coast	Inter and supra-tidal habitats	Chust et al. (2009)	Passive flooding	Shoreline and habitat changes over 50 years obtained from a database of aerial images, field surveys and LiDAR data.	Tide gauge	SLR accounts for smaller changes in habitats than human impacts
French Mediterranean Provence	Pocket beaches	Brunel and Sabatier (2007, 2009)	Passive flooding	4 field and aerial surveys over 103 years	Tide gauge	SLR accounts for 60% of shoreline retreat
French Mediterranean Camargue	Open wave dominated beaches	Brunel and Sabatier (2009)	Passive flooding	4 shoreline positions over 103 years from maps, field surveys and aerial imagery	Tide gauge	SLR accounts for 10% of shoreline retreat
Suffolk coast, UK	Unconsolidated soft cliffs	Brooks and Spencer (2012)	Several cliff erosion models	4 shoreline positions over 125 years from maps, field surveys and aerial imagery	Tide gauge	SLR a major marine driver

[a] Denotes studies that attempt to quantify sediment mass or volume changes.

general case (i.e. considering any type of geomorphological context such as cliffs, beaches, etc.), this approach therefore assumes that the observed shoreline changes over a given period of time ΔS can be written:

$$\Delta S = f_{\xi}(\Delta\xi) + f_{\boldsymbol{\Phi}}(\boldsymbol{\Phi}) \quad (1)$$

where, $\Delta\xi$ is the observed relative sea level changes over the same period of time, $\boldsymbol{\Phi}$ are other forcing factors causing shoreline changes, and f_{ξ} (respectively $f_{\boldsymbol{\Phi}}$) are functions predicting the shoreline retreat given $\Delta\xi$ (respectively $\boldsymbol{\Phi}$).

The key issue in model based approaches remains the choice of the functions f_{ξ} and $f_{\boldsymbol{\Phi}}$, to which shoreline change observations are compared. Presently, no coastal model is able to reproduce all of the hydro-sedimentary processes in the coastal zone at yearly to decadal timescales (Hanson et al., 2003). Instead, several types of models have been developed for solving specific aspects of coastal evolution (De Vriend et al., 1993; Amoudry and Souza, 2011). This covers a wide range of tools, from idealized models, which describe particular processes at the relevant spatial and timescales of interest (e.g. Ashton et al., 2011; Ranasinghe et al., 2012; Ranasinghe et al., 2013), to self-organization models (Coco and Murray, 2007) and full-process models (e.g., Delft3D, Lesser et al., 2004), or combinations of them. While some full-process models have been used to model the future response of coastal zones to sea-level rise (e.g., Storlazzi et al., 2011; Dissanayake et al., 2012), Table 3 (column 4) shows that the most represented models in the reviewed studies remain either (1) passive flooding models, which assume that the coastal morphology does not change as sea level rises, and represents the submergence of low lying areas, located below a given elevation (Brunel and Sabatier, 2007,2009; Chust et al., 2009), or (2) simple idealized morphodynamic models, describing the general expected behavior of shorelines in response to sea-level rise.

Besides one study using cliff retreat models (Brooks and Spencer, 2012), the morphodynamic model used most commonly in this context remains the Bruun rule (Bruun, 1962; Table 3, column 4). The Bruun rule assumes the landward translation of a fixed cross-shore profile as sea level rises and predicts shoreline retreat as much as 10 to 50 times the sea-level rise, depending on the beach slope. The model assumes that the cross-shore sediment budget remains unchanged (neglecting longshore sediment processes), so that with shoreline retreat, the volume of sediment eroded from the shoreline is redistributed in the nearshore profile. Beside the lack of simple alternatives (Cooper and Pilkey, 2004a), the main advantage of this law is its simple analytical form, which relates shoreline changes due to sea level changes with the beach slope β and the change in relative sea levels $\Delta\xi$:

$$f_{\xi}(\Delta\xi) = \Delta\xi / \tan\beta. \quad (2)$$

Attempts to validate this rule provide contrasting results, with some studies showing good agreement between Brunn rule predictions and observed shoreline changes (Mimura and Nobuoka, 1996), and others showing sites where the Bruun rule is not able to hindcast shoreline mobility (List et al, 1997). This has raised concerns about the applicability of this rule in general (Cooper and Pilkey, 2004a; Davidson-Arnott, 2005). In the studies reviewed in Table 3, the purpose of using the Bruun rule was to evaluate the contribution of sea-level rise to recent shoreline mobility. By considering common values of β (a few degrees) and $\Delta\xi$ (currently a few millimeters per year), Eq. (2) indicates that $f_{\xi}(\Delta\xi)$ will be far less significant than $f_{\boldsymbol{\Phi}}(\boldsymbol{\Phi})$ in Eq. (1), as soon as the observed shoreline changes ΔS exceed 1 m/year (Stive, 2004). On the contrary, coastal sites where the impacts of sea-level rise will appear most significant based on such model approach will be those with moderate shoreline changes.

3.2. Existing applications

Two types of approaches have been used to overcome the difficulties mentioned above. First, recognizing the lack of accuracy of existing functions f_{ξ} and the need to validate them, two studies proceeded as follows (Zhang et al., 2004; Brooks and Spencer, 2012): first, they characterized the geomorphological context of the considered coastal sites; then, they discussed the applicability of the considered coastal model f_{ξ}; finally, they interpreted their results in a specific geomorphological context to evaluate the role of sea-level rise in causing shoreline retreat. This approach can be exemplified by the study by Zhang et al. (2004): they studied the eastern coast of the USA, where coastal sea-level rise and shoreline retreat are known from long-term and repeated observations. They compared shoreline change observations in coastal sites with similar sedimentary dynamics that were relatively unaffected by direct human activities. They found that coastlines located near to 35°N display the highest sea-level rise rates (because of subsidence induced by the Global Isostatic Adjustment), but also the quickest shoreline retreat rates, and they obtained a correlation between the shoreline retreat observations and the estimations from the Bruun rule. They interpreted these results as both a validation of the Bruun rule and as a clear indication of the importance of sea-level rise in shoreline erosion. A key step in the process of applying the Bruun rule is the selection of consistent subsets of coastal sites and knowledge of the other factors possibly affecting shoreline changes.

The second way to overcome the difficulties mentioned in the previous sections has been to estimate all components of the sedimentary budget at the site of interest. The sediment budget includes gains and losses due to processes such as longshore sediment transport gradients, storm wind and wave induced cross-shore sediment transport, and sediment inputs and sinks from adjacent geomorphic systems (e.g., dunes, inlet deposits), or from human activities (e.g. dredging, beach nourishment, coastal defenses). In studies reviewed in Table 3, this partitioning of the sediment inputs and outputs into several components has been estimated either (1) by quantifying the contribution of each process to the sediment budget (e.g., Allen, 1981; Inman and Dolan, 1989; Aagaard and Sørensen, 2013); or (2) through a semi-quantitative analysis of the sediment budget, consisting in evaluating the importance of all factors possibly causing shoreline changes through an analysis of correlations between the temporal or spatial variations of shoreline changes and each given factor (e.g. Corbella and Stretch, 2012); or (3) finally through a qualitative assessment of the contributing factors to the sediment budget (e.g. Brunel and Sabatier, 2007, 2009).

To validate the approach as a whole, two independent evaluations of the sediment budget can be compared (Allen, 1981; Aagaard and Sørensen, 2013): the first being the sum of each quantified contribution, the second being an estimate of the amount of transported sand, obtained by interpreting observed shoreline changes. For example, Aagaard and Sørensen (2013) consider that $f_{\boldsymbol{\Phi}}(\boldsymbol{\Phi})$ in Eq. (1) is the sum of longshore sediment transport gradients, cross-shore sediment transport due to the mobility of submarine bars eventually transported to the dune by winds (Aagaard et al., 2004), and external inputs due to artificial nourishment:

$$\Delta(S) = f_{\xi}(\Delta\xi) + f_{\boldsymbol{\Phi}}(\boldsymbol{\Phi}) = \frac{\Delta\xi}{\tan\beta} + f_{Longshore} + f_{Cross-shore} + f_{External}. \quad (3)$$

Aagaard and Sørensen (2013) obtain good agreement between the two independent estimates of $\Delta(S)$ and $\frac{\Delta\xi}{\tan\beta} + f_{Longshore} + f_{Cross-shore} + f_{External}$ at the Skallingen inlet. In this case, the authors explicitly present a closed budget of the relative contribution of each process accounting for sediment transport at the study site. Since this coastline is evolving rapidly, the effects of sea-level rise, as calculated by the Bruun rule, remain small compared to the other terms in Eq. (3). This approach, which compares the sum of each term accounting for sediments gains and losses in the active coastal profile with shoreline change observations is referred to as the 'sediment budget approach' hereafter.

3.3. Limitations and potential for improvements

All model-based approaches assume that the model uncertainties are significantly lower than the predicted response of the coastal system to sea-level rise. In the case of coastal impacts of sea-level rise, it is questionable that any coastal model can meet the required accuracy: the passive submersion model is not considering the dynamic response of sediments to changes in sea-level rise, and coastal morphodynamic models that take into account sea-level rise explicitly (in the reviewed studies: mainly the Bruun rule) are neither accurate enough nor validated sufficiently to reach the accuracy required for shoreline change attribution studies. These questions regarding the accuracy of available modeling tools constitute the major limitation of this type of approach. The sediment budget approach, which compares observed shoreline changes to the sum of the contribution of each individual process, is certainly an improvement of the approach. However, it is important to remember that other coastal evolution models ($f_{\Phi}(\Phi)$ in Eq. (1)) also have uncertainties. For example, the sediment budget approach generally requires using a longshore sediment transport model, which can also have large uncertainties (Cooper and Pilkey, 2004b). Furthermore, the sediment budget will not be necessarily closed for each sedimentary cell: for example, Inman and Dolan (1989) identify two sedimentary cells where the residuals are significant, suggesting an onshore sand transport from the shelf.

To what extent could coastal models be improved, and, consequently, could model-based approach receive more attention in the future? While a lot of progress has been made in recent decades in medium-term process-based morphodynamic models (Amoudry and Souza, 2011; Kaergaard and Fredsoe, 2013), as including taking into account sea-level rise and specific processes along tidal inlets (e.g. Stive and Wang, 2003; Ranasinghe et al., 2012, 2013), it is important to note that: (1) errors in hydrodynamic modeling are exponentially amplified in empirical sediment transport formulas, and (2) shoreline prediction errors are amplified in time. For example, the sediment transport formulas of Soulsby–van Rijn (Soulsby, 1997) and of Bailard (1981) are commonly used in 2DH morphodynamic models. Silva et al. (2009) performed an intercomparison of sediment transport formulas in current and combined wave-current conditions, showing that these models reproduce the overall trends, but exhibit strong differences depending on the environment: depending on the formula, sediment transport rate values vary between one and two orders of magnitudes. This emphasizes the limited prospects of immediate improvements in process-based models.

4. Discussion: limitations of existing approaches and ways forward

Independent of the method used, studies attempting to evaluate the impacts of sea-level rise on shoreline changes require at least shoreline change data and coastal sea-level rise. However, the availability of shoreline change and relative sea level rise measurements extending over several decades, as analyzed by Zhang et al. (2004) remains an exception. This part first reviews common difficulties regarding the collection and analysis of the data encountered by studies reviewed in this paper. It then examines the applicability of the reviewed methods to different types of coastal environments (Table 4) and suggests approaches to select appropriate coastal sites at which these methods could be tested in future studies.

4.1. Shoreline data

In many of the world's coastal areas, no shoreline change data are presently available (Bird, 1985; Cazenave and Le Cozannet, 2014): this is the case in areas currently considered as highly vulnerable to sea-level rise, such as the Pacific atoll islands (Mimura, 1999), as reminded by Webb and Kench (2010) and Ford (2012). Hence, the studies reviewed in Tables 1 to 3 often report difficulties in accessing a sufficient amount of shoreline position observations to reconstruct the historical shoreline variability over pluridecadal timescales (e.g., Ford, 2013). They also report difficulties related to the heterogeneity of shoreline change data and the associated uncertainties. When shoreline changes are sufficiently large (several tens of meters), remote sensing can enable semi-automated comparison of large scale areas by providing a common protocol for all sites (Shearman et al., 2013), thus making comparisons consistent. However, most observed shoreline changes are presently much smaller (less than 1 m/year according to Bird (1987)). In this case, shoreline change observations can only be obtained by means of repeated in-situ surveys, analysis of aerial or satellite high-resolution photographs at several time intervals, or a combination of both approaches. In addition, different shoreline proxies can be used (Boak and Turner, 2005) (e.g., top or base of cliffs, dunes or coastal defenses [sea wall, quay, dykes…], limit of permanent vegetation, water

Table 4
Summary of the methods used to evaluate the recent impacts of sea-level rise on shoreline changes and their applicability to different types of coastal environments.

Level 1	Level 2	Level 3	Types of coastal environment to which the method applies	Number of reviewed studies
Data based approach	Analysis of spatial patterns of sea-level rise and of shoreline changes	Qualitative analysis of shoreline change observations and likely causative factors	– Any homogeneous set of similar coastal systems (e.g. Shearman et al.,2013) – Or information aggregated from multiple word's surveys (Bird, 1985)	5
		Statistical analysis over large datasets	– Homogeneous set of similar coastal systems (e.g. Zhang et al., 2004) – Or database of heterogeneous coastal systems, used within a statistical approach that allows to consider the relative importance of other factors causing shoreline changes (e.g. Gutierrez et al., 2011)	4
	Analysis of temporal dynamics of sea-level rise and of shoreline changes	–	Any single coastal site	5
Model based approach	Based on passive flooding	–	Application limited to coastal environments not affected by morphological changes	3
	Based on a coastal evolution model (morphodynamic model accounting for sediment transport)	Idealized models:	– Beaches, depending on the applicability of the idealized model at the site of interest – Cliffs (Brooks and Spencer, 2012)	6 (5 using the Brunn rule)
		Others: self organization models, full process models, combination of models	Model dependant	None

level reached for given atmospheric and oceanic conditions). Therefore, in the general case where shoreline changes are relatively moderate, obtaining satisfactory accuracy in shoreline change data is often challenging (Crowell et al., 1991). An additional difficulty affects advanced statistical approaches (such as those of Gutierrez et al. (2011)): they require shoreline change data collected locally by means of different techniques and then aggregated at several scales, which raises concerns about the consistency. To summarize, both methods discussed in parts 2 and 3 require shoreline data that are sufficiently accurate, but also temporally and spatially consistent. Most studies are currently limited by the short timescale of shoreline change observations, which should ideally cover multiple decades to adequately identify the impacts of sea-level rise on shoreline position. Improvements can be expected here with the increase in the availability of existing datasets, the creation of sustained coastal observatories, and the accumulation of very high resolution satellite imagery.

4.2. Relative sea-level rise data

A second important limitation is the lack of knowledge of contemporary coastal sea-level rise. Most of the studies reviewed in this paper used tide gauge data near the coastal sites of interest to estimate the relative sea-level rise at the coast (Tables 1, 2 and 3). However, even when tide gauges seem relatively densely distributed along the coastline, the possibility of highly local vertical land movement cannot be ruled out (e.g., Ostanciaux et al., 2012; Santamaria-Gomez et al., 2012). Most studies rely on the hypothesis that no differential ground movement affects the tide gauge or site of interest, i.e. that tide gauge measurements are representative of relative sea-level rise along the coast of interest. This hypothesis is, in practice, difficult to verify when no geodetic data are available. Some studies considered that vertical ground motions can be neglected for their specific sites, and therefore focused on the climate component of sea-level rise (e.g. Yates et al., 2013; Shearman et al., 2013). These studies require information about the climate-induced regional variability of sea-level rise (Meyssignac and Cazenave, 2012). A primary source of information is satellite altimetry, which provides the regional sea-level rise rates since 1993, with a precision reaching about 1.5 mm/yr to 2.5 mm/yr at a single point. Studies considering shoreline changes over longer timescales require reconstructions of past sea-level rise (Church et al., 2004; Llovel et al., 2009; Meyssignac et al., 2012). These reconstructions presently provide rates of sea level changes back to 1960. Fig. 4 provides the reconstruction of Meyssignac et al. (2012) and the associated uncertainties (estimated as the root mean square error of three different reconstructions). This figure highlights that the errors are spatially variable and are higher in locations affected by more rapid sea level changes from 1960 to 2010. A cautious use of these datasets can thus provide part of the necessary information for data-based studies (part 2). However, it is necessary to take into account the uncertainties, particularly where there is high regional variability in sea-level rise, where several reconstructions disagree, or where few or less reliable tide gauge data constrain the reconstruction.

In the most general case, studies attempting to explore the relation between sea-level rise and shoreline mobility face the difficult task of separating the different components of relative sea-level rise at the

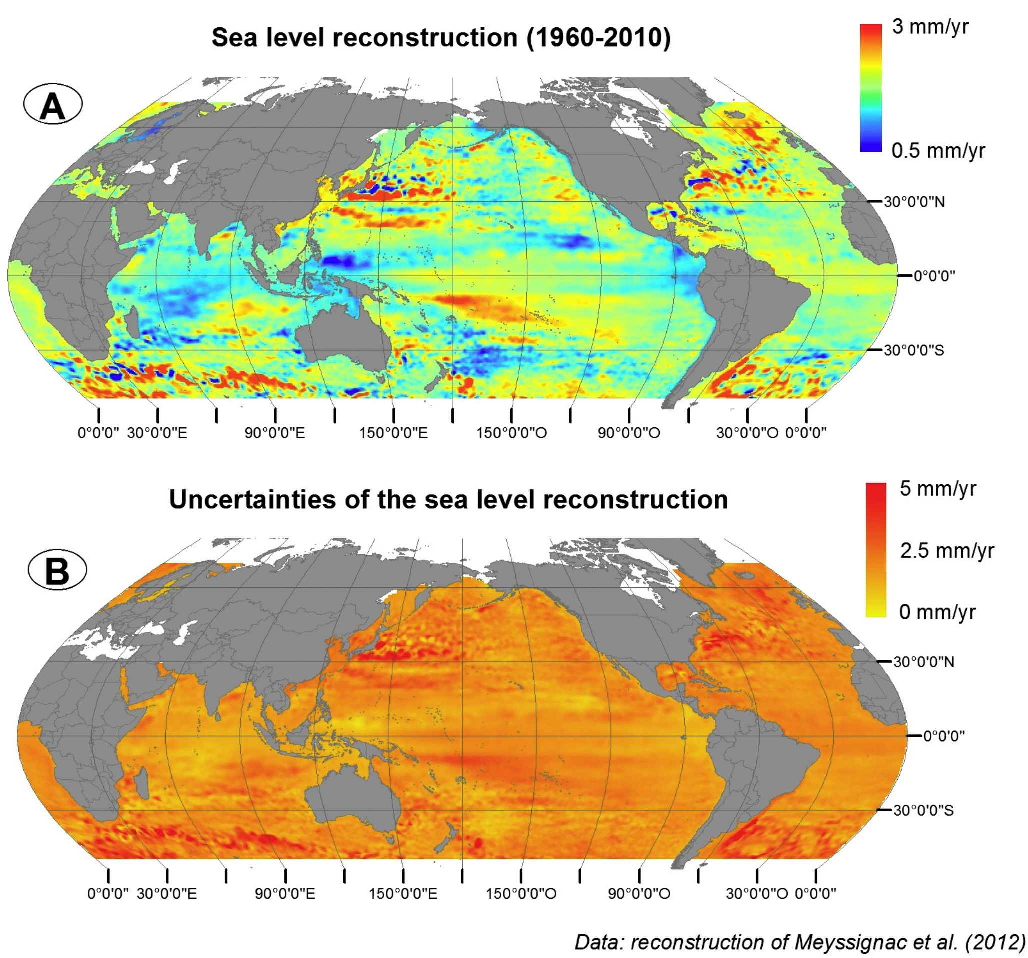

Fig. 4. Sea-level reconstructions from 1960 to 2010 and the associated uncertainties. Data from the Meyssignac et al. (2012) reconstruction.

coast. Some well-established techniques exist to evaluate vertical ground motions along the coasts (Table 5). Information and data such as sea level reconstructions, GIA models, permanent GPS networks, leveling surveys (Lenotre et al., 1999), evidence of former shorelines (e.g., Pirazzoli and Montaggioni, 1988), geological or stratigraphical observations (e.g., Dawson et al., 2012) or markers of recent changes in mean water levels (e.g., Evelpidou et al., 2012) are becoming increasingly available and can allow the evaluation of the different components of sea-level rise separately (e.g., Brooks et al., 2007). In many cases, it would be useful to combine these sources of information in order to have a clear understanding of the spatial and temporal dynamics of vertical ground movements at relevant timescales (e.g., Kooi et al., 1998). These efforts would be useful to progress in evaluating recent impacts of sea-level rise to shoreline changes.

4.3. Applicability of the reviewed methods

While the methods reviewed in parts 2 and 3 have a broad range of potential applications, their relevance depends on the type of coastal environment of interest (Table 4). Independent of the method considered, an important criterion for selecting coastal sites is their expected vulnerability to sea-level rise. Thin sandy barrier islands affected minimally by longshore drift and human actions should be suitable sites to monitor in this context. However, this first criterion raises numerous issues since many types of coastal sites that may be a-priori vulnerable to sea-level rise (e.g. deltas, sandy inlets) are also affected by dynamic sedimentary processes.

In observation-based approaches analyzing spatial patterns of shoreline and of sea-level rise changes, a set of similar coastal sites must be selected. However, identifying similar coastal sites is difficult in general due to the number of aspects to consider (e.g., tidal range, exposure to waves, coastal geomorphology, lithology). We note that the analysis based on Bayesian networks attempts to undertake this categorization task. Repeated careful applications of this approach with large coastal databases may help to identify appropriate typologies of coastal systems with respect to their vulnerability to sea level rise.

Future model-based approaches can continue to be improved upon with a more careful analysis of the model assumptions and selected study sites. For example, the Bruun rule assumes that cross-shore transport processes dominate shoreline changes on beaches, and this model should not be applied in other coastal environments or at sites with complex sediment transport fluxes. Here, the limited number of available modeling tools (passive submersion and the Bruun rule) restricts the application of the method to sites that are either unaffected by morphological changes or to sites where cross-shore sedimentary processes dominate, such as some bay-beaches or linear beaches affected by perpendicular waves.

Finally, only a very limited number of studies actually attempted to evaluate the role of sea-level rise in past shoreline changes (Fig. 5). More efforts to collect and analyze historical shoreline evolution data and a more systematic approach to select sites to monitor are likely required to make progress in this field. Along with other approaches, such as experiments in waves tanks (Dubois, 2002) or modeling experiments (e.g., Storlazzi et al., 2011; Dissanayake et al., 2012), these efforts may stimulate advancing in understanding the complex linkages between sea-level changes and shoreline mobility.

5. Conclusion: results and recommended methods

Collectively, the reviewed studies do not provide observational evidence that contemporary sea-level rise has been a major driver of shoreline retreat over the last few decades. Instead, the results are different from site to site, suggesting the significance of the local coastal setting. The results of these studies suggest that no general conclusions can be drawn relating sea-level and shoreline changes on a global scale without taking into account the characteristics of each site. Hence, three

Table 5
Main approaches for evaluating components of sea-level rise at the coast and their use in reviewed studies.

Approach	Method	Examples of use in studies listed in Tables 1 to 3	Sea level component addressed	Temporal timescale and resolution of ground movement revealed	Main limitations
Metrology	Use of nearby tide gauge measurements	Many studies (e.g. List et al., 1997; Brunel and Sabatier, 2009; Webb and Kench, 2010)	Relative sea level change at the coast, at the point of interest	Decades to a century (longer time series in a few locations)	Point-like data: it is assumed that no local ground movement affects the area of interest
	Interpolation of nearby tide gauge measurements	A few studies (Zhang et al., 2004; Gutierrez et al., 2011).	Relative sea level change at the coast along the shoreline	Decades to a century (longer time series in a few locations)	It is assumed that no local ground movement affects the area of interest
	Satellite altimetry	Shearman et al. (2013)	Climate component of sea level changes	Two decades (since the late 90s)	If used alone, it is assumed that no local ground movement affects the area of interest
	Permanent GPS	None	GIA and more local vertical ground movements	Two decades (since the late 90s)	Point-like data
	Leveling data (Lenotre et al., 1996; Lenotre et al., 1999)	None	Differential ground movements	Decades to a century, depending on the temporal resolution of surveys.	Availability of data; only adapted to ground movements with low frequency spatial patterns
	Satellite aperture radar interferometry techniques (InSAR)	None	Differential ground movements	Two decades (Since 1993)	Availability of data, site specific technical applicability of the method
Modeling	GIA modeling	None	GIA	Years to millennia	Some disagreement between GIA models
	Sea level reconstructions	A few studies (Yates et al., 2013)	Climate component	Presently about 60 years	Some disagreement between reconstruction models
Observations	Use of geological evidence of past sea levels	A few studies (Yates et al. (2013), referring to Pirazzoli and Montaggioni (1988))	Relative sea level change at the coast, at the point of interest	A few centuries to millennia	Site dependent; requires interpretation of data and assumptions on the representativeness of observed evidence
	Sediment core accumulation rates (e.g., Stanley, 1990)	None	Relative sea level change at the coast, at the point of interest	A few centuries to millennia	
	Archeological sites (e.g., Stanley and Toscano, 2009)	None	Relative sea level change at the coast, at the point of interest	A few centuries to millennia	

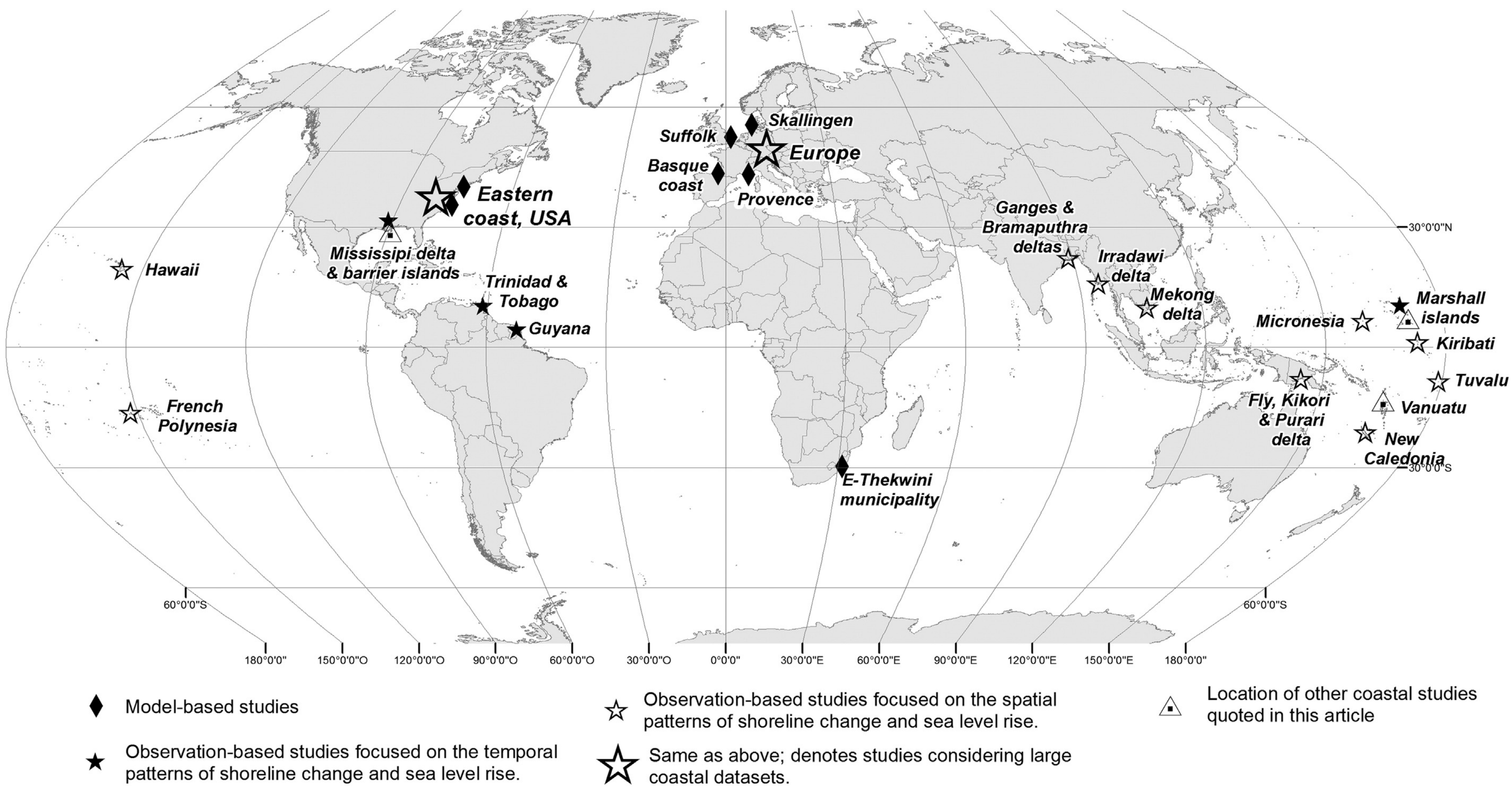

Fig. 5. Location of coastal studies cited in this article. The map shows the studies falling within each type of approach analyzed in parts 2 and 3 (Tables 1, 2 and 3), as well as several studies not directly focused on detecting the role of decadal sea-level rise impact [in the Torres Islands (Vanuatu): Ballu et al. (2011); on the Mississippi delta barrier islands: List et al. (1997); at Majuro (Marshall islands): Ford (2012)].

major conclusions can be drawn from this review: (1) even with the recent acceleration in global sea-level rise, local variability in sea-level change rates, coastal geomorphology, and forcing factors limits making broad conclusions about the impacts of sea-level changes on shoreline position in different coastal environments; (2) future studies can benefit from expanding coastal sea-level and shoreline change datasets, as well as additional observations of other important coastal processes; and finally, (3) it is necessary to clearly define the assumptions and limitations associated with each approach before selecting the appropriate method to apply at a selected site. While the present review has focused on shoreline changes, other studies have suggested that sea-level rise impacts on other coastal hazards such as extreme coastal flooding (e.g. Zhang et al., 2013) or saline intrusions in coastal aquifers (e.g., Werner and Simmons, 2009) are similarly highly variable depending on the local coastal morphology and hydrogeology.

From a methodological point of view, two main types of approaches have been identified to evaluate the recent impacts of sea-level changes on shoreline changes: the first (observation-based approach) analyzes the spatial or temporal patterns of sea level and shoreline changes to examine if a relation can be found. The second (model-based approach) compares shoreline change observations to the outcome of a coastal model. Both methods have specific limitations: the underlying hypotheses on the dynamics of changes in observation-based approaches, and the lack of accuracy of shoreline change models in model-based studies. They also have common limitations due to a lack of coastal shoreline and sea-level rise data. However, they provide the basic methodological framework for detecting the impact of sea-level rise on shoreline changes.

Future studies using both approaches can benefit from extending existing coastal sea-level rise and shoreline change datasets by increasing both the length of the time series, as well as the temporal and spatial resolution. In addition, observation-based approaches can be improved upon by including a wider range of data concerning coastal processes, such as wind and wave measurements, tidal fluctuations, and sediment sources and sinks (e.g. longshore fluxes, offshore losses, inputs from rivers). While many sites may currently be in the first phase of adaptation to sea-level changes, in which other coastal processes dominate present day shoreline changes, continued observations may allow the detection of the transition to the second phase, in which the impacts of sea-level rise become dominant. Even during this second phase, a uniform response of a coastal system should not be expected, as suggested by variable coastal responses to the 3 m rise of the Caspian Sea level from 1977 to 2001 depending on local sedimentation processes and human actions (Kakroodi et al., in press).

In recent decades, detection and attribution have become an important concern in climate change science, and these efforts are progressively spreading into the field of the expected impacts (IPCC WG2 AR5 Ch 18: Cramer et al., in press). In climate change science, the use of climate models is recommended in detection and attribution studies (Hegerl and Zwiers, 2011). However, when considering the case of sea-level rise impacts on shorelines, there are two major differences: first, the natural variability often exceeds the signal to be identified; secondly, the accuracy of the available coastal models is still insufficient to allow estimating with confidence the relative effect of sea-level rise on shoreline evolution everywhere (their skills limiting their application to specific coastal settings) (part 3). These difficulties in applying model based approaches to evaluate the recent impacts of sea-level rise on shoreline changes suggest that further attention should be given to observation-based approaches.

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